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Enhancing severe accident management through research

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Abstract. After the Fukushima Daiichi accident, a new wave of research projects aiming at enhancing severe accident (SA) management was launched under different international frameworks. This was the case of MUSA (Management and Uncertainties of Severe Accidents), AMHYCO (Towards and enhanced Accident Management of the H2 and CO combustion risk) and SOCRATES (Assessment of liquid Source Term for accidental post management phase), which under the frame of H2020 and HEUROPE EURATOM were devised to optimize different aspects of Severe Accident management. MUSA explored how bringing uncertainties quantification in the Severe Accident analysis might provide sounder insights into effects and timing of accident management actions. AMHYCO brought new insights into combustion risk management, particularly during the ex-vessel phase of the accident, by combining in a selective manner different analytical approaches and data on recombination and combustion of gas mixtures (i.e., H_2/CO/air/steam). SOCRATES is hitting accident management related to liquid source terms, with emphasis in the long-run of the accident. This paper describes the major outcomes of the projects and outlines what should come next for an efficient application of the insights gained in the accident management.

1 Introduction

Accident management is at the core of the fourth level of the defence-in-depth concept on which nuclear safety relies on. Its objective is to prevent severe damage to the reactor core and, in the case of non-postulated accidents, to mitigate their consequences. This purpose requires a thorough understanding of severe accident phenomena and evolution. Despite the gigantic progress made since the TMI-2 accident in 1979, the huge complexity associated with severe accidents (i.e., strong coupling and huge diversity of phenomena at different scales; harsh boundary conditions; long transients; technology-specific scenarios; ...) makes the current knowledge still incomplete and uncertain.

Right after the Fukushima Daiichi accident, a number of research projects on nuclear safety were launched. Most of them clustered around at least one of two major goals: understanding the Fukushima Daiichi accidents unfolding; and, enhancing accident management as far as possible. In the frame of the EURATOM program of the European Commission several projects were proposed. MUSA (Management and Uncertainties of Severe Accidents), AMHYCO (Towards and enhanced Accident Management of the H_2 and CO combustion risk) and SOCRATES (Assessment of liquid Source Term for accidental post management phase), are three good illustrations of projects targeting an improvement of accident management from different angles.

MUSA was devised to set a sounder severe accident analysis method to assess better timing and effect of any accident management action, mainly related to Source Term (ST). AMHYCO was addressed to fill in the existing gap in combustion risk when H_2/CO/H_2O/CO_2/Air-gas mixtures (i.e., ex-vessel phase of the SA) by extending the recombination and combustion databases and bringing a multi-level approach to containment analysis. Finally, SOCRATES has been outlined to strengthen long-term accident management measures related to liquid ST. Next sections describe the main features and outcomes of the three projects and their outcomes potential to impact accident management. It should be stressed that these three projects got a strong commitment to education at MSc and PhD levels; several students have participated and benefited from opportunities offered.

2 MUSA: quantifying uncertainties in severe accident analysis

2.1 Motivation

Numerical simulation of severe accidents (SA) is a central element of the safety demonstration of any Nuclear

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Power Plant (NPP). Along decades, results from severe accident research have been capitalized in severe accident integral codes built on validated models and correlations [1]. Despite the wide range of models implemented, the extensive validation, and the enhanced numerical methods, their estimates are associated with uncertainties of different kinds. Their identification and understanding would provide meaningful insights for a better assessment of nuclear safety, such as time and failure mode of safety barriers (cladding, boundary of reactor coolant system, and containment), effectiveness of accident management actions, and prediction of the radiological Source Term (ST) released to the environment.

Uncertainty quantification (UQ) was proposed in the area of thermal-hydraulic modeling as part of the Best Estimate Plus Uncertainty (BEPU) methodology to analyze Design Basis Accidents (DBA) and, more specifically, to the licensing of the Emergency Core Cooling System (ECCS) [2]. Much of the progress made in BEPU has fed some attempts of application in the severe accident field but, given the intrinsic and major differences between both domains, BEPU application in severe accident modeling has been proved far more complicated. Uncertainties when modeling an accident scenario grow when moving from the DBA to the severe accident realm, and the experimental database available supporting any uncertainty characterization is far less complete than in the case of DBAs. Hence, the quantification of any kind of uncertainties in severe accident codes estimates is a challenging undertaking.

Nonetheless, the promising insights gained from using such an approach [3] was the driver, in 2019, of the EURATOM HORIZON-2020 project on Management and Uncertainties of Severe Accidents (MUSA). Coordinated by CIEMAT and participated by 29 international organizations, MUSA orchestrated a broad application of the UaSA[1] methodology in severe accident analysis [4].

2.2 Short project description

MUSA generic objective was to quantify uncertainties in severe accident code estimates when modeling reactor and spent fuel pool scenarios of GEN II, GEN III designs for the prediction of the radiological source term (ST). Therefore, ST-related Figures Of Merit were used when applying SA-adapted uncertainty quantification (UQ) methodologies. Meeting the above objective required:

- Identifying key severe accident processes/phenomena affecting the source term and quantification of their associated uncertainties.
- Characterizing uncertainties of key parameters affecting source term, including those related to accident management.
- Preparing and assessing UQ methods (sensitivity analyses included) applicable to the severe accident field and formulating recommendations on how to use them.
- Trialing UaSA methodologies against risk-dominant severe accident sequences in reactor and spent fuel pools.
- Pinpointing steps in the UaSA application that might require further investigation before proposing a systematic methodology.
- Listing remaining code uncertainties associated with source term estimates and their interaction with accident management measures that would be worth addressing.

MUSA activities were structured in two major blocks: one devoted to the provision of essential elements for the application of BEPU (i.e., uncertainties of model parameters in severe accident codes' decks; and analytical tools assembled in computational frames enabling propagation of uncertainties and analysis of the results of the calculation campaigns); and the other to the application of the BEPU methodologies. About two-thirds of the total workforce (625 person-month) was spent to application, including hands-on training on a simplified accident scenario (the PHEBUS-FPT1 test) [5], "full-scope" applications to a range of reactor designs (PWR, BWR, VVER, CANDU, etc.) [6], and a Fukushima Unit 4-like spent fuel scenario [7,8].

MUSA had specific features that made it different from any previous application of UaSA in the Severe Accident field [9,10] and are worth highlighting:

- The broad range of competencies and experience on severe accident phenomena from all over the world that was involved, merging different perspectives (i.e., Technical Support Organizations (TSO), utilities, research centers, and academia).
- The source term focus stemmed naturally from the ultimate goal of severe accident codes and was inspired by the uncertainties around the source term in the Fukushima Daiichi accidents [11].
- The integrating nature encompassing both in-reactor and spent fuel pool scenarios, with a substantial diversity in water-cooled reactor designs (Gen. II and Gen. III).
- The strong link with the communities dealing with Probabilistic Safety Assessment (PSA) level 2, emergency response, environmental consequence analysis, and AM, through the project Advisory Board and the End-Users Group.

2.3 Major outcomes

A thorough description of MUSA outcomes may be found in [12]. As high-level outcomes, MUSA highlighted two major facts:

- Application of UaSA in severe accident analysis is doable. However, it demands indispensable elements (i.e., a reliable database of uncertain parameters, a computational infrastructure based on severe accident codes, UQ analytical tools and tailored scripts to analyze the huge database resulting, and sound severe accident and statistical skills), which have been developed to some extent within MUSA. Engineering judgment can be mentioned among that essential elements.

[1] Uncertainty and Sensitivity Analysis.

- A systematic application of UaSA, though, needs further work to develop a guiding procedure for practitioners. This entails investigating strengths/weaknesses of any assumption/hypothesis needed, and most importantly, the best way to handle the massive information resulting from any UaSA realization campaign.

In short, a systematic methodology needs to be consolidated for a sound assessment of uncertainties associated with severe accident modelling.

More specifically, a synthesis of specific outcomes is given next:

- **Uncertainty database**. A matrix containing the selected variables, parameters and models together with its uncertainty ranges has been built. More than 450 uncertain parameters directly related to source term have been characterized through their reference value, lower and upper bounds (uncertainty range) and Probability Density Function (PDF). Additionally, another about 150 parameters, indirectly involved in ST variables, were also characterized.
- **Methodologies**. Integral severe accident codes (i.e., MELCOR, ASTEC, AC2, MAAP, etc.) were coupled with pre-existing statistical tools (i.e., DAKOTA, SUNSET, SUSA, RAVEN or URANIE) or *ad-hoc* ones. MELCOR 2.2/DAKOTA and ASTEC 2.2/SUNSET were the most widely used. Most applications set realization sizes based on the approximation of order statistics (usually referred to as the Wilks' theorem [13]).

Some generic lessons were derived concerning the methodology: the robustness and computational efficiency of the best estimate plant model are paramount; the size and composition of the uncertain parameters set is crucial and should be based on a balanced choice between comprehensiveness and potential impact; expert judgment is indispensable at several steps of the entire process, particularly the selection of input deck parameters and the analysis of the realization campaign; no single technique is optimum for sensitivity analysis and the use of several is highly recommended.

Several methodological issues remained with no specific solution. To name a few: the suitability of purely random techniques to sample input parameter PDFs (versus other options like Latin Hypercube Sampling, LHS); the consideration of failed cases in the realization campaign; the determination of the number of parameters set; etc. These aspects demand further work to explore consequences and to substantiate recommendations.

- **Applications to real scale scenarios.** As for reactor scenarios, MUSA addressed not just a large variety of reactor designs (PWR, BWR, VVER, etc.), but also scenarios (LB- and MB-LOCAs, SBOs, SGTRs, etc.), with and without accident management actions. Table 1 shows an example of the PWR database. It is important to realize the huge diversity considered in the project in so many regards when coming to UaSA applications. In the first column (NPP) those of Gen. III generation are highlighted in red. In the second column, a variety of scenarios are addressed, according to acronyms used in the accident literature (LB, large break; MB, medium break; LT, long term; SBO, Station BlackOut; LOCA, loss of coolant accident) and all those related with piping breaks are highlighted. In the 4th and 5th columns, colours match codes and statistical tools as they are more often coupled.

Likewise, the employed methodologies were also quite diverse. Beyond the specific severe accident codes and UQ tool used, the size of the sets of uncertainty parameters and figures of merit were notably diverse. As for the number of realizations, even if most times the order statistics was adopted and the number of calculations were around 100, occasionally some partners ran hundreds of cases (300, 900). This broad database demonstrates the ability achieved to bring UaSA into severe accident scenarios, no matter the reactor design, the accident sequence, or the methodology used.

Figure 1 shows two examples from independent calculations for a similar but not identical scenario.

As for UaSA applications in spent fuel pool scenarios, they were to a good extent similar to the reactor applications in terms of employed methodologies. A single scenario, though, was addressed: a loss-of-cooling accident in a spent fuel pool similar to the one in Unit 4 of Fukushima Daiichi NPP with a limited damage of spent fuel rods. Major differences were noted in the best estimate, coming from diversity in scenario modelling. In comparison, the variability observed in the results of the BEPU application were moderate.

- **Sensitivity analyses**. Most times correlations of figures of merit with input parameters were sought through correlation coefficients, which proved to be a too simple approach and provided just a partial view of potential correlations. Occasionally, more advanced techniques were intended, but as said above further work is required in this area.

2.4 Recommendations

As stated in the previous section, some additional work remains to be done to settle a systematic methodology that allows a sound assessment of uncertainties associated with severe accident modelling:

- Completion of the MUSA parameters uncertainty database. A peer review, inclusion of additional model parameters and an extension to components and safety systems parameters should be conducted.
- Assembly of a systematic procedure to apply UaSA into severe accident modelling. Remaining issues in the UaSA procedure like bifurcations, outliers, realizations crashes and many others (i.e., noding, numerics, numerical noise, etc.) need to be worked out.
- Investigation of advanced techniques for data analysis. A move from traditional correlation coefficients to more advanced techniques and methods (i.e., stepwise regularization; Lasso regularization; multiple regression; etc.) should be conducted to maximize the insights gained when interpreting their results.

Table 1. PWR scenarios database.

NPP	Scenario(s)	SAM	SA Code	U&S Tool	#UPs	#FoM	# Calcs. for UQ
PWR-1000	LBLOCA		MELCOR	URAINE			
PWR (Surry)	SBO		MELCOR	DAKOTA	24	3	93
HPR-1000	LBLOCA		ASTEC	SUNSET	5	8	100
PWR-900	SBO		MELCOR	DAKOTA	8	1	130
PWR 4-Loops	LT-SBO at Low P		RELAP/SCDAP	IUA2.0	19	26	124
PWR (Surry)	ELAP w/o SAM ELAP+SAM	AC restored at RPV failure	MAAP	Python	232	12	500
KONVOI	MBLOCA+SBO		AC2	SUSA	81	10	100
PWR-900	SBO+Loss of aux.FW	Sump flooding, CFVS	ASTEC	SUNSET, Python	43	12	100
APR-1400	C-SGTR by SBO		MELCOR	DAKOTA	6	4	300
KONVOI	MBLOCA w/o SAM MBLOCA+SBO MBLOCA+SAM	CFVS	ASTEC	KATUSA	18	6	900 (300*3)
PWR-1100	SBO+SGTR	SG re-flooding	MELCOR	DAKOTA, Python	17	2	100
CAP-1400	LOCA+SBO		MAAP	DAKOTA			
PWR-1000	SBO	Cavity flooding+CFVS	MELCOR	Python	15	6	111

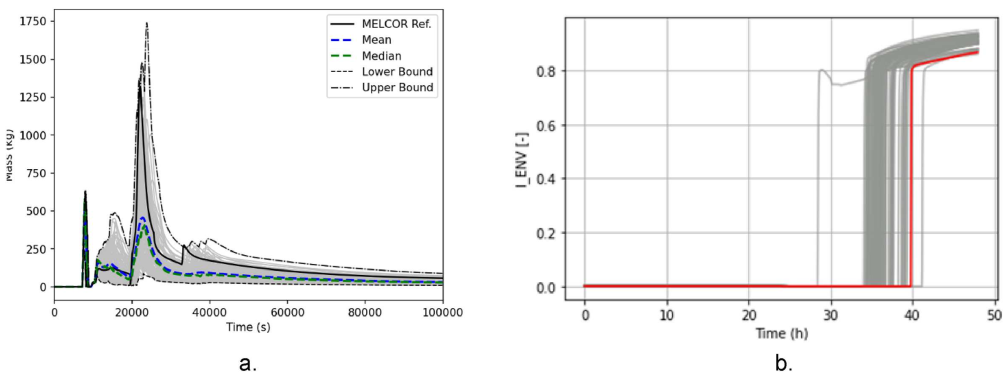

Fig. 1. Examples of 2 figures of merit for two independent PWR-SBO UaSA analysis. (a) In-containment airborne aerosol. (b) Iodine release to the environment.

- Extensive application of the consolidated methodology. Demonstration of the procedure against Gen. II and Gen. III reactor designs, and including Water-cooled SMRs and ATFs, should be carried out with the focus on the uncertainties effect on accident management measures and vice versa.

3 AMHYCO: gaining insights into ex-vessel combustion risk

3.1 Motivation

Combustible gases generated during a severe accident are among the most serious threats to the containment integrity. An appropriate management of the associated risk is paramount to prevent the potential release of significant amounts of radioactive material to the environment. Since the Fukushima accident in Japan in 2011, various additional measures to reduce the risk of containment failure have been undertaken by nuclear power plants (NPPs) within the European Union. These measures include also dedicated severe accident mitigation hardware like Passive Autocatalytic Recombiners (PARs) and a Filtered Containment Venting System (FCVS), if not already installed previously. To this end, several projects have been recently conducted under the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) framework to address remaining gaps regarding hydrogen distribution, combustion, and efficiency of PARs to prevent combustion. On the other hand, the Severe Accident Management Guidelines (SAMGs), which guide the reactor operators on how to handle the response of the nuclear power plant against severe accidents, need to be regularly updated and include knowledge gained from international research, including recent and ongoing projects.

3.2 Short project description

The main objective of the AMHYCO project is to propose innovative enhancements in the way combustible gases are managed in case of a severe accident in currently operating reactors. AMHYCO will contribute to this objective by improving the understanding of H_2/CO combustion risk and incorporating this knowledge into SAMGs. To reach this main objective, the project proposes a methodology that is organized in several steps that will be briefly described.

As a first step, several knowledge gaps related to hydrogen (H_2) and carbon monoxide (CO) recombination and combustion during a severe accident in PWRs

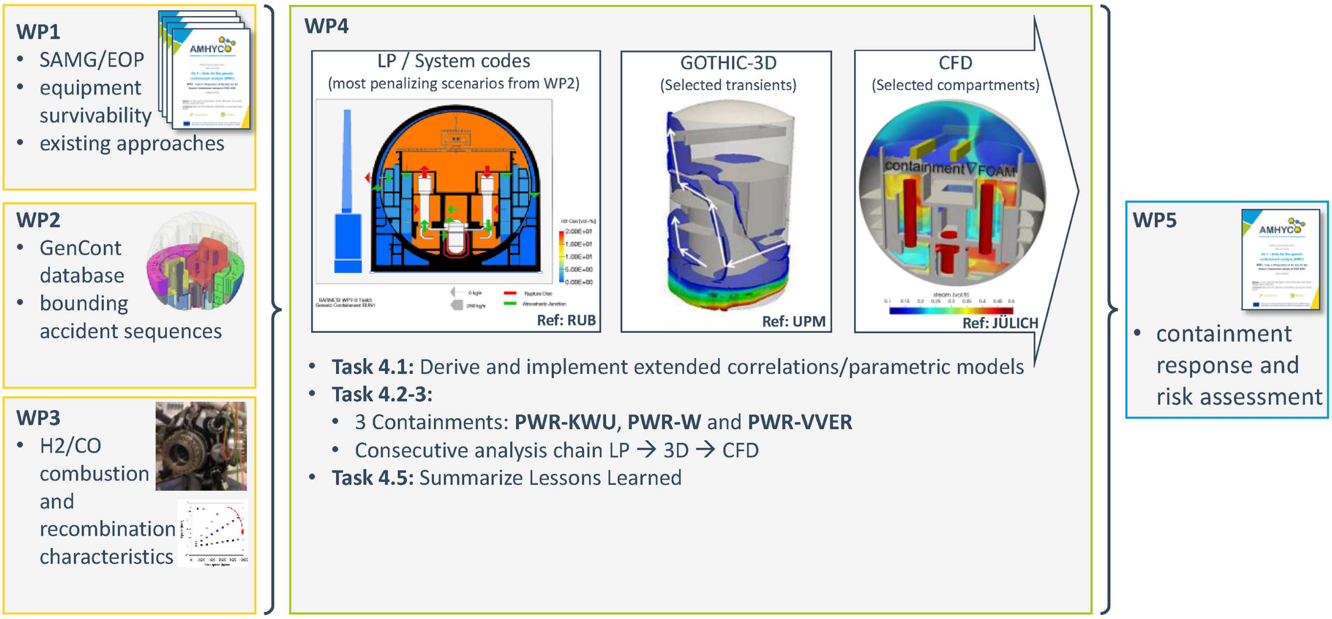

Fig. 2. Integration of numerical and experimental activities in AMHYCO.

were identified. In particular, the areas peer reviewed were: recombine behavior in severe accident late phase; containment risk management in EOPs and SAMGs; H_2/CO combustion risk engineering correlations; criteria for containment equipment qualification and instrumentation surveillance. The work was summarized in [14].

As a next step, relevant combustion risk sequences were identified and characterized for different PWR designs (Western, KWU and VVER) so that a scenario database was built. The information gathered was the basis for the experimental investigation on recombination and combustion of H_2/CO mixtures and for testing different analytical approaches (LP; 3D, and CFD; LP standing for Lumped Parameter). The work was summarized in [15].

Once the sequence identification was done, data for development and validation of numerical models and simulation tools was obtained with experimental setups in the fields of combustion of H_2/H_2O/CO mixtures in the air as well as explosion risk mitigation using passive autocatalytic recombiners (PARs).

With both the experimental and numerical information, the bases of a comprehensive analytical assessment that provided insights for a review and potential extension of the SAMGs and EOPs were built. To do so a generic containment model was developed, allowing the inter-comparison of analytical approaches being used for containment analysis. Figure 2 displays the conceptual scheme this particular step within the outline of the project.

As the last part of the project, potential enhancements of safety procedures (e.g. EOPs) and severe accident management guidelines (SAMGs) are being explored to reduce the H_2/CO combustion risks to the containment, taking as a basis both the experimental and the numerical results obtained before.

3.3 Major outcomes

At this time, the last steps of the project have not ended yet, so the outcomes summarized next are considered preliminary, but insightful.

The review of the existing PWR SAMGs pointed to some interesting facts: the existing requirements (only a few countries do have quantitative criteria) addresses only in-vessel conditions, and their extension to ex-vessel conditions need to be established; likewise, the mitigation means should be proved useful beyond the in-vessel phase; few existing SAMG recommendations concern the use of safety systems (spray and coolers) in the late phase of a SA. Besides, it is worth noting that in-containment monitoring systems are not devised to measure CO.

From the pool of PWR sequences analysed, just a few posed challenging combustion conditions; i.e., flammable mixtures ($X_{H_2} + X_{CO} > 9$ vol.%; $X_{O_2} > 5$ vol.%; $X_{H_2O} < 55$ vol.%) were identified, particularly in the ex-vessel phase. Figure 3 shows the entire pool of sequences classified according to the reactor design; note that those meeting the flammability conditions are highlighted in red. The sequences posing a higher combustion risk resulted to be: SBLOCA ($5\,cm^2$) and LBLOCA, for PWR-W; MBLOCA ($80\,cm^2$) for PWR-KWU; and SBO with sprays for PWR-VVER. Two major factors heavily condition this finding: the availability of safety systems capable of condensing steam during the ex-vessel phase since they result in a boost of combustible gas content; and the PARs performance, which causes O_2 depletion in the ex-vessel phase and makes gas composition exit the flammable region of the Shapiro diagram in the long run, even if combustible gas content is well over 9 vol.%.

Through the extensive experimentation conducted new insightful data and correlations have been produced under conditions not explored before, which were used in the

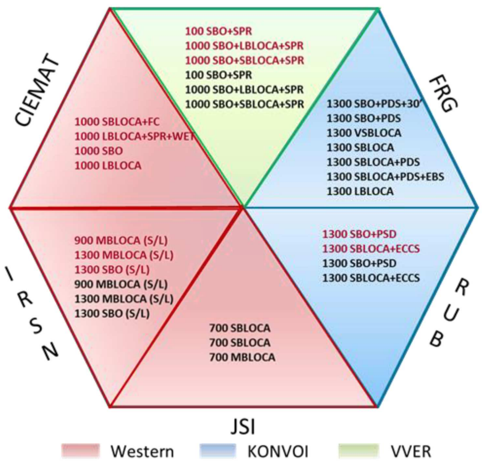

Fig. 3. PWR accident sequences modeled.

advanced containment analyses conducted. In particular, a new correlation for PAR performance was developed and new flammability limits and combustion regimes were identified for with H_2/CO mixtures.

Containment analyses of two of those sequences noted of interest in terms of combustion risk have been conducted: unmitigated Small (S) or Medium (M) break Loss of Coolant Accidents (LOCA) and Station Blackout (SBO) / Total loss of auxiliary power (TLAP) accidents. The former allowed studying the impact of sprays and/or fan coolers on PARs performance; the latter, even if inerted by steam, brought in the analysis the potential interaction of FCVS and PARs.

A three-level approach has been adopted: lumped parameter analysis (MELCOR and ASTEC), which sets a sort of reference or baseline containment analysis; 3D modeling with GOTHIC, which was brought in just for the most penalizing scenarios to assess whether 3D flow patterns might provide additional insights concerning combustion risks; and, based on the 3D observations, a CFD approach will be adopted (containmentFOAM and ANSYS Fluent) for specific compartments and time windows identified as of potential combustion risk interest

The increasing level of spatial details achieved with the different codes is being utilized to assess the view of the accident from the control room (available sensors) against the full insights provided by the simulations to propose an upgrade of the severe accident instrumentation.

3.4 Recommendations

According to what was stated in the previous section, the SAMGs should be further developed to include specific actions that take into account the combustible gases risk when making a decision, especially for the late phase. As it was found, there are several sequences for each PWR technology addressed (Western-type; KWU; VVER) that suggest a multi-level approach to assess any decision to be made concerning combustion risk. For example, the combustion risk should be treated differently in case of high concentrations of steam or oxygen starvation.

The lack of a thorough understanding of $H_2/CO/H_2O/CO_2$ $/O_2/N_2$ mixtures in terms of combustion heavily handicaps the capability to make sound decisions when the time comes. Likewise, a good characterization of PARs behavior in every aspect and condition should be pursued since their passive performance does affect multiple aspects of the accident scenario.

Even if still pending of a sound settlement, the studies so far indicate the convenience of using a multi-level analytical approach to inform decisions related to combustion risk. LP codes provide a useful integral perspective but are "blind" to local conditions, sometimes of high relevance for accident management (including instrumentation reliability). In turn, 3D and CFD guidance in accident management should be accompanied with uncertainties quantification whenever feasible.

4 SOCRATES: preventing liquid source terms

4.1 Motivation

The primary focus in nuclear accident research has historically been on airborne radioactive releases, as these can spread rapidly over large areas, posing immediate risks to populations and environment. Consequently, most research and modelling efforts have centred on predicting the behaviour of airborne radioactive materials. However, contaminated liquid, particularly in emergency cooling systems that may circulate highly radioactive water, is also critical, especially in the post-accident phase, as it is the case in the Fukushima Daiichi site [16]. Failure of these cooling systems, which may be located inside or partially outside the containment building depending on reactor design, could result in loss of cooling or release of contaminated liquid into the environment. Although the importance of liquid radioactive sources is widely recognized and supported by recent studies, research in this area has been limited, leaving gaps in understanding radionuclide behaviour in liquid form during accidents.

4.2 Short project description

The SOCRATES project addresses critical gaps in our understanding of the liquid source term during severe nuclear accidents and offers innovative solutions to mitigate and monitor the release of radionuclides into the environment. This topic has a significant increase of interest after the Fukushima Daichi NPP accident, regarding the large volumes of contaminated water to be treated, but also the behavior of radionuclides in these waters. By advancing scientific knowledge and technological capabilities, SOCRATES directly contributes to the mid-to-long-term accident management of nuclear power plants [17], enhancing safety, environmental protection, safe waste management and public well-being. This is important for the existing large LWRs and even more important for the future SMRs located in cities nearby populated areas.

SOCRATES is composed of three major parts. The focus in the first part is on reviewing the current knowledge on the liquid source term phenomena in severe NPP accident context. It will cover past accidents, code capabilities to simulate liquid source term phenomena, knowledge from other simulation tools (like geochemical tools) and databases, and summarizing work on critical analysis of experimental and simulation results. The current possible measures and severe accident management actions to manage liquid source term will be reviewed.

The second part focuses on experimental research. However, the first task is to define the experimental conditions using also feedback from the above-mentioned literature review, and set the experimental plan. From there on, SOCRATES focuses on studying the evolution of liquid phase chemistry and properties under various conditions. It will be extended to cover also interaction of fission products (e.g. Cs, Sr). Progressing towards more demanding experiments, leaching of ceramic material models, nuclear fuel pellet, prototypic metallic corium and real corium will be examined. As a parallel study, SOCRATES develops innovative sorbent materials for radionuclides from design to synthesis, characterization and testing. Fortum's patented NURES®technology, ion exchange material, will be used as a reference material to compare the sorbent performance with. Furthermore, development of a miniature size radiochemical laboratory will be performed by testing radionuclide detection from liquid and sorbent samples.

The third part of SOCRATES focuses on defining the key chemical processes for Cs, Sr and U in sump. The models developed with the experimental data from SOCRATES will be implemented in severe accident codes (e.g. AC2, ASTEC). Selected severe accident scenarios will be calculated. The project outcomes will be summarized in recommendations to regulators and nuclear community.

Besides the research activities, SOCRATES results communication, dissemination and exploitation is crucial. It includes for example preparation of scientific publications, researcher mobilities and preparation of educational materials based on SOCRATES results.

4.3 Major outcomes

Still at its initial stage, the major outcomes foreseen in SOCRATES will be:

- **Comprehensive State-of-the-Art Report.** SOCRATES will review the current understanding of the liquid source term in SA, with emphasis on evaluating the capabilities of existing accident analysis codes (e.g. predict chemical speciation in the liquid phase, both in soluble and insoluble forms). The report will set this baseline and will add on the project results in every respect that is being investigated.
- **Experimental database.** SOCRATES is building a database on water chemistry during nuclear accidents by cataloging potential materials (e.g., concrete, paint, metals) that could interact in different accident scenarios. Experiments will place major emphasis in investigating: specific fission products behavior, such as cesium (Cs) and strontium (Sr), in water; fuel debris leaching, including tests with real corium samples. This database will support the development of computer models.
- **New computer code models.** SOCRATES will develop computer code models capable of predicting and managing the potential release of radioactive materials in liquid form during severe nuclear power plant accidents. Different scenarios are to be addressed involving fission products behaviour in aqueous environments during SA. In the end, the intention is to validate the models developed and integrate them into European safety analysis codes (e.g., ASTEC, AC2) supporting further accident management actions.
- **Innovative Absorbent Materials.** Mitigating the release of radioactive materials in liquid form during severe accidents requires innovative and effective clean-up technologies. Promising absorbents are being identified (i.e., zeolites, clays, MOFs, and silicas) and their performance is planned to be demonstrated, including their own synthesis. Additionally, Fortum's NURES®material, used previously in Fukushima, will serve as a benchmark for comparing new absorbents.
- **Innovative Miniature Size Radiochemical Laboratory.** A novel miniature-size radiochemical laboratory (the size of a credit card) is being developed in SOCRATES to allow the early measurement of radionuclides of interest e.g. Cs and Sr.

4.4 Key elements

SOCRATES has recently started, and the first step will entail supporting a sound definition of the experimental conditions and test matrices for the experimental work that will support the mentioned model development.

From SOCRATES results, recommendations for LTO and management of liquid source term, particularly in the long-run, are expected.

5 Final remarks

Outcomes from safety research projects developed within the EC EURATOM framework, are supporting further reinforcement of the fourth level of defence-in-depth through gaining insights into different related aspects. Next, some highlights summarizing those coming from the MUSA, AMHYCO and SOCRATES projects:

- Determining uncertainties in severe accident analysis is feasible and would allow accident management actions to be better allocated in time and characterized in terms of effectiveness. Nonetheless, a sound consolidated methodology deserving full credit is still missing and should be developed and demonstrated against current running technologies and forthcoming technology innovations (water-cooled SMRs and ATFs, included).
- Accident management actions related to combustion risk should address actual prevailing conditions in containment, including the ex-vessel phase of the accident ones, by stretching the boundary conditions of the database to produce reliable models. Having characterized experimentally and analytically those scenarios has allowed more accurately assess the effect of different accident management actions. However, the

variety of conditions still demands further research to support some of the actions proposed and/or proposed new ones.

- An effective management of the liquid source term demands an accurate picture of water interaction with active materials, particularly Cs and Sr, under broad ranges of boundary conditions and a search for materials capable of absorbing the largest possible fraction of potential compounds in liquid leakages. An integration of these aspects in a holistic AM plan would allow optimizing any mitigation means that might be put in place.

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Conflicts of interest

The authors declare that they have no competing interests to report.

Data availability statement

Data associated with this article can be disclosed upon request through project coordinators, and availability will depend on the request's objectives and the use foreseen by the applicant.

Author contribution statement

Luis E. Herranz – Conceptualization, project administration, funding adquisition, supervision, visualization, and writing of the MUSA project. Paper structure and writing of generic sections. Gonzalo Jiménez – Conceptualization, project administration, funding adquisition, supervision, visualization, and writing of the AMHYCO project. Review of paper generic sections. Teemu Kärkela – Conceptualization, project administration, funding adquisition, supervision, visualization, and writing of the SOCRATES project. Review of paper generic sections.

References

1. L.E. Herranz, R.O. Gauntt, Severe Accident Analyses: A historical review from the very early days to the near-term future, Nucl. España **395**, 12 (2018)
2. U.S. Rohatgi, J.S. Kaizer, Historical perspectives of BEPU research in US, Nucl. Eng. Des. **358**, 110430 (2020), ISSN 0029-5493, https://doi.org/10.1016/j.nucengdes.2019.110430
3. S. Ghosh et al., Summary of the uncertainty analysis for the state of the art reactor consequence analysis project, NUREG-2254 (2022)
4. L.E. Herranz et al., The EC MUSA Project on Management and Uncertainty of Severe Accidents: Main Pillars and Status, Energies **14**, 4473 (2021), https://doi.org/10.3390/en14154473
5. F. Mascari et al., Ann. Nucl. Energy **196**, 110205 (2024), ISSN 0306-4549, https://doi.org/10.1016/j.anucene.2923.110205
6. S. Brumm et al., Uncertainty quantification for severe-accident reactor modelling: Results and conclusions of the MUSA reactor applications work package, Ann. Nucl. Energy **211**, 110962 (2025), ISSN 0306-4549, https://doi.org/10.1016/j.anucene.2024.110962
7. O. Coindreau et al., Uncertainty quantification for a severe accident sequence in a SFP in the frame of teh H-2020 project MUSA: First outcomes, *The 10th European Review Meeting on Severe Accident Research (ERMSAR2022)*, Karlsruhe (Germany, 2022)
8. O. Coindreau et al., Uncertainty quantification for a severe accident sequence in a SFP in the frame of the H-2020 project MUSA: First outcomes, Ann. Nucl. Energy **188**, 109796 (2023), ISSN 0306-4549, https://doi.org/10.1016/j.anucene.2023.209796
9. M. Khatib-Rahbar et al., A Probabilistic Approach to Quantifying Uncertainties in the Progression of Severe Accidents, Nucl. Sci. Eng. **102**, 219 (1989)
10. R. Gauntt, Uncertainty Analyses Using the MELCOR Severe Accident Analysis Code, NEA 6053, Session-III-Applications-to-Uncertainty-Assessment-on-Severe-Accidents, Aix-en-Provence (France, 2007)
11. S. Suehiro et al., Development of the source term PIRT based on findings during Fukushima Daiichi NPPs accident, Nucl. Eng. Des. **286**, 163 (2015), ISSN 0029-5493, https://doi.org/10.1016/j.nucengdes.2015.02.005
12. L. Herranz et al., Major achievements of the EC MUSA project, *The 11th European Review Meeting on Severe Accident Research (ERMSAR2024)*, Stockholm, Sweden, May 13-16 (2024)
13. S. Wilkss, Determination of Sample Sizes for Setting Tolerance Limits, Ann. Math. Stat. **12**, 91 (1941), https://doi.org/10.1214/aoms/1177731788
14. A. Bentaib, Critical assessment of key elements of combustible gases management in containment. AMHYCO deliverable D.1.1 (2022), https://amhyco.eu/resources/
15. L. Herranz, J. Fontanet, High combustion risk sequences. Identification and characterization, *The 10th European Review Meeting on Severe Accident Research (ERMSAR2022)*, Karlsruhe, Germany, May 16-19 (2022)
16. W. Men, Discharge of contaminated water from the Fukushima Daiichi Nuclear Power Plant Accident into the Northwest Pacific: What is known and what needs to be known, Mar. Pollut. Bull. **2173, Part A**, 112984 (2021), ISSN 0025-326X, https://doi.org/10.1016/j.marpolbul.2021.112984
17. NEA, Impact of Short-Term Severe Accident Management Actions in a Long-Term Perspective, Paris, NEA/CSNI/R(2000)8 (2000)

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